Blue mussel spat availability and settlement on longlines in a Faroese fjord

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Summary

Blue mussel farming is currently not an industry in the Faroe Islands. However, they are abundant in the coastal waters around the islands and previous trials have shown a good farming potential. Blue mussels are a low trophic species that show a great potential to increase the food production from the sea in a sustainable manner. Blue mussels are also well tested candidates in Integrated multitrophic aquaculture and various other environmental impact mitigation trials.

This study was conducted in collaboration with the fish farming company Hiddenfjord, who wish to test the mitigation potential of blue mussels in relation to fish farming. Since the primary purpose of the blue mussel farms was mitigation, they chose to test low labour intensive setup with natural spat collection and self-thinning.

The spat availability, settlement and growth on longlines was investigated from 2018 to 2020. Planktonic Bivalvia larvae were collected with 80 µm and 150 µm mesh plankton nets. In the 80 µm net the majority of the larvae were smaller than reported sizes at settlement. In the 150 µm net the majority of the larvae were around the reported sizes at settling (240-350 µm). The larval abundance was significantly higher in the 80 µm net with peak abundances around 1500 ind m^{-3}.

The abundance of planktonic larvae indicated two peak spawning period, the first in May and June and the second in August and September. However, the interannual variation was high. The mean shell length of larvae captured with the 80 µm net increased steadily until mid-June early-July whereafter it dropped and gradually increased again, indicating that settlement from the first spawning mainly occurred at this time.

Three kinds of long lines were investigated Fuzzy rope (FR), Trawl (TR) and a flat rope commonly used as spat collectors at mussel farms in Denmark "Svendsker band" (SB). The settlement on the SB was very poor. The other two showed higher settlement, although the mussel density was quite low after the first settlement compared to similar studies.

In 2019 which showed better settlement than 2018, there were 395 ind. m^{-1} on the FR at 4 m depth and 262 ind. m^{-1} on the TR. The growth during the first year was similar to previous observations in the Faroe Islands, while it was somewhat smaller during the second and third year. The growth was higher than observed in Nova Scotia, Canada, but significantly lower than observed in the Limfjorden, Denmark where phytoplankton availability is considerably higher than the Faroe Islands.

During the second year, new spat settled on the ropes, and the blue mussel size at 4 m depth indicated that the older blue mussels were predated or lost due to mechanical disturbance, while the older blue mussels remained on the rope at deeper depths.

After the lines had been deployed for three years, the TR showed highest blue mussel abundances and largest sizes, with 1000 ind. m^{-1} at 12 m depth and 633 ind. m^{-1} at 4 m depth, which is within the range of other longline trials. The abundance on the FR was 373 and 573 ind. m^{-1} at 4 and 12 m depth, respectively. Also, the TR showed a cleaner blue mussel culture compared to the FR, where there were quite a variety of other species present on the lines.

Introduction

Blue mussel farming can be considered an environmentally friendly method of marine feed production since no feed is added to the environment to grow them. They are filter feeders that feed directly on phytoplankton and other suspended material. Thus, blue mussel farming is removing organic matter from their environment rather than increasing the organic and nutrient load which is the case in e.g. fish farming.

Due to the localized nature of intensive fish farming and limited water exchange in coastal areas, dissolved organic matter (POM) and nutrients from the fish farms may cause negative near and far-field ecological effects. Integrated multi-trophic aquaculture (IMTA), where the waste from one aquatic species serves as source (fertilizers, food) for other lower trophic species is one proposed method to mitigate the ecological effects of nutrient and organic enrichment from aquaculture systems. Blue mussels (*Mytilus edulis*) have shown great mitigation potential due to their high filtration capacity (Chopin et al., 2012). In the wild, blue mussels play an important role as filter feeders, removing bacteria, heavy metals and toxins from the water. They are a foundation species in the intertidal community that create habitat and enlarge the diversity of life supported by a location (Martinez-Albores et al., 2020; Sorte et al., 2017). IMTA promotes economic and environmental sustainability by converting by-products from fed organisms into harvestable crops, thereby reducing eutrophication, and increasing economic diversification.

There are no commercial blue mussel farms in the Faroe Islands and one of the obstacles has been the legislation that has prevented farming of multiple species in the same region, where regions covered entire fjords and areas outside the fjords. In 2019 major changes were conducted in the aquaculture legislations and now farming multiple species in the same region is possible and the plan is to offer selected sites for blue mussel farms in the near future.

One common blue mussel farming method is passive collection of wild spat by deploying spat collecting lines in the water at the time of mussel settlement. This method will likely be the preferred farming method in the early stages of blue mussel farms in the Faroe Islands.

In this study the spatial and temporal distribution of planktonic Bivalvia larvae was investigated in the fjord Sørvágsfjørður, and settlement on three types of commercially available spat collectors was tested.

Previous studies of blue mussels in the Faroe Islands

Blue mussels are abundant in Faroese fjords and previous investigations have shown potential for blue mussel farming by wild spat collection (Gaard, 1986; Jensen and Patursson, 2011).

A Master thesis by Gaard (1986), investigated possibilities for blue mussel cultivation using settling ropes and spat collectors in the fjord Trongisvágsfjørður in 1984-85, and a BS thesis by Jensen and Patursson (2011), with Gaard as supervisor investigated spawning, larval abundance, settlement and growth of mussels at 4 different sites in the Faroe Islands from spring to autumn 2010.

Gaard (1986) reported a relative long spawning period, from May-June to mid-August, by investigating gonads. Larval settlement occurred approximately four weeks after spawning. Planktonic larvae were found throughout the spawning period with peak abundances in June and August-September, at one of the innermost stations in the fjord, where the abundance was highest. Both peaks showed an abundance of ~ 350 ind. m^{-3} collected with a 150 µm mesh plankton net.

Measurements on larval settlement were conducted with spat collectors, where sections of spat collecting ropes were deployed during the various seasons enabling investigations on the temporal spat settlement and also settling ropes that were deployed during the whole investigation period. Both methods showed highest settlement at the inner part of the fjord which decreased rapidly outwards to the more exposed part of the fjord. Spat collector measurements from summer of 1984 showed a peak average of ~3200 ind. m^{-1} at the innermost part of the fjord. Measurements were from 0.5 to 6.5 m depth, and although the spat was present at all depths, the majority was found at ~4 m depth. In the innermost part of the fjord the peak settlement was in early August, whereas further out spat collection was highest in June-July, with a dip in July-August, and a secondary peak in August-September. These measurements corresponded well to the pelagic larval abundance, showing peaks in June-July and in August-September.

Settling rope measurements showed a peak of ~5100 ind. m^{-1} in the innermost part of the fjord, and numbers decreased rapidly further out of the fjord, with ~1000 ind. m^{-1} at mid-fjord, and with almost no settlement on the outermost ropes ~4 km away from the innermost station. Spat was present on the ropes from the surface to ~14 m depth, and there was a high variability in spat abundance as a function of depth.

Jensen and Patursson deployed spat collecting ropes and ropes with one year old mussels at four different sites in the Faroe Islands (Kaldbaksfjørður; a 7 km long fjord, Skálafjørður; a 15 km long fjord, Sundalagið Str. and Sundalagið Ey.; two sites at a narrow strait highly influenced by tidal currents). During spring and summer 2010, samples of larval abundance, temperature, salinity and chlorophyll *a* measurements were taken and gonads of mussels in one fjord were collected. Samples of mussels were also collected for DNA studies to check if *M. galloprovincialis* was present in the Faroes. With these data the growth, the settling of mussels and the spawning of mussels were investigated as well the larval abundance and the environmental factors which influence these.

There is no record of other Mytilus species in the Faroe Islands than *Mytilus edilus*, since the only conducted DNA analyses only found *Mytilus edilus* (Jensen and Patursson, 2011).

Mussel larvae were collected in the upper ~6 m with a 20 µm mesh plankton net. The actual volume of filtered seawater could not be measured, and therefore the actual information on larval concentrations is not available. However, since the same sampling procedure was used every time, the information on relative abundance, can be comparable between dates and sites. Planktonic larvae were investigated from April 18th 2010 to September 13th 2010. 10 mm thick ropes were used for the larval settlement investigations. The ropes were deployed at three different dates (in May and June). The blue mussel abundance on the ropes was investigated on September 25th 2010 in Skálafjørður and on October 28th 2010 at the other locations.

The gonad index (0-5) showed that the mussels were fully mature and spawning was about to begin in mid-April. The gonad index was high (above 3) until early July, when it dipped to below 1, and stayed low the rest of the summer.

The larval abundance was highest in late June and early July. The total number of larvae was highly variable between sites with Sundalagið showing significantly higher abundance in the samples than Kaldbaksfjørður and Skálafjørður (Contrast ANOVA, p<0,01).

There was a steady increase in planktonic larval sizes throughout the spring and summer. They found an increase of larvae larger than 0.29 mm from mid-June, whereas from April to the beginning of June almost all the larvae were below 0.29 mm. However, on May 17th and on June 20th most small larvae (0.12-0.2 mm) were observed as well.

Kaldbaksfjørður and Skálafjørður showed the highest larval settlements on the ropes, whereas Sundalagið had lowest numbers. The settling reached a top in Skálafjørður with ~4500 ind. m^{-1}.

Chlorophyll *a* concentrations were investigated as a proxy for food availability. The average concentration from May to September was 4.9 µg L^{-1} which is really close to the optimal concentration of 5 µg L^{-1} for maximum blue mussel growth according to Clausen and Riisgård (1996).

Materials and methods

Study site

Sørvágsfjørður is located on the westernmost main island Vágar in the Faroe Islands. The fjord is 5 km long, less than 1.5 km wide and the maximum depth is 55 m (Figure 1). The seawater circulation in the inner part of the fjord is influenced by tidal forces, with semidiurnal water level changes up to 2 m at neap tide, and estuarine circulation driven by water runoff from the ~31 km^2 catchment area, most of which is uninhabited and uncultivated. In general, the stratification in Faroese fjords is weak and the water masses are easily mixed by wind forces. This implies that nutrients are readily mixed into the euphotic zone and the primary production is usually high during the whole summer (Gaard et al., 2011).

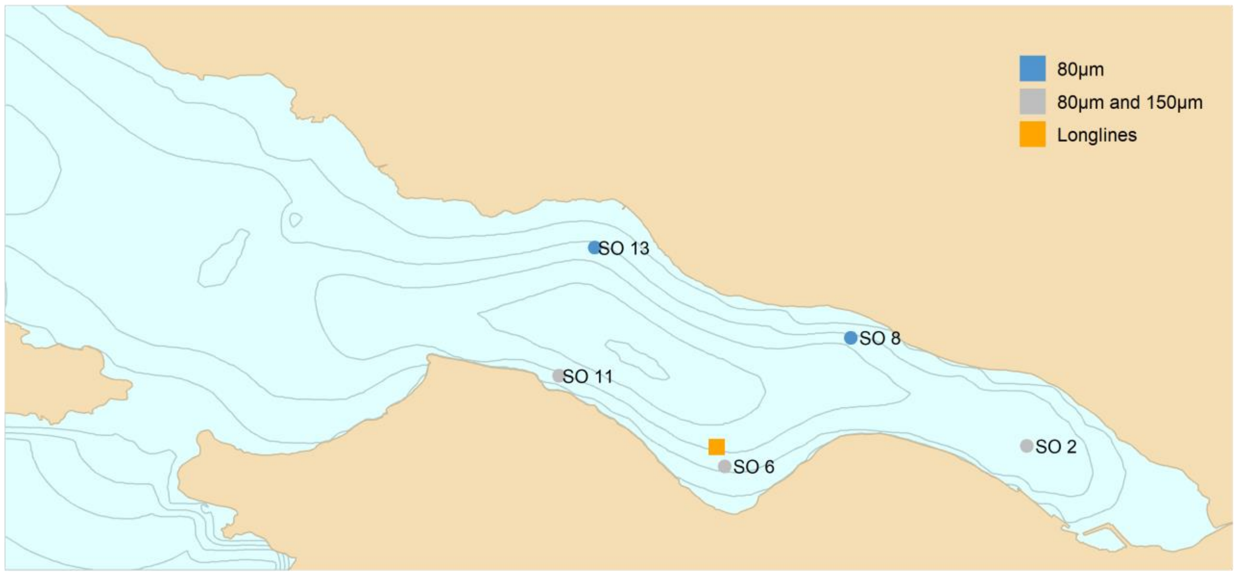


Figure 1 Map of Sørvágsfjørður showing the plankton sample locations and the location of blue mussel lines.

Generally, there is an estuarine circulation in the inner part of the fjord, with an upper outflowing layer of seawater mixed with runoff water and a lower layer of denser seawater flowing in from the open sea outside the fjord. Additionally, flow out of the fjord tend to be mainly at the north side of the fjord, and inflow on the southern side due to influence of the Coriolis forces (Figure 2). However, strong winds can disrupt this flow pattern and even temporarily reverse it (á Norði and Patursson, 2017). In areas with a relatively shallow pycnocline and unstable weather conditions, such as in many high latitudinal Atlantic fjords, the hydrographic properties are temporally highly variable. Wind strength and direction, precipitation, and tides may vary substantially within a short time, and affect the hydrographic conditions (mixing, upwelling, stratification and depth of the pycnocline). Such fjords can therefore often be considered as highly dynamic systems (Gaard et al., 2011).

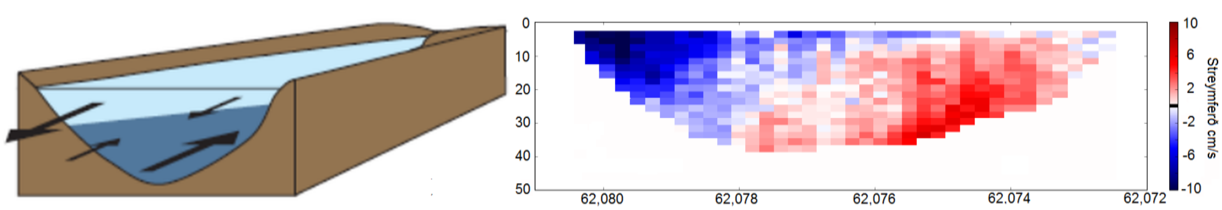


Figure 2 Left) Typical flow pattern in Faroese fjords dominated by estuarine circulation influenced by the coriolis force form ; from (Hansen, 2000)*. Right) Flow in Sørvágsfjørður measured in a calm weather situation demonstrates estuarine. Read is inflow, blue is outflow; from* (á Norði and Patursson, 2017)*.*

Anthropocene sources of organic matter and nutrients to the fjord are from the small population of 1200 inhabitants in the two villages Sørvágur and Bøur, and fish farming activity. One fish farm is located in the outer part of the fjord, where Atlantic salmon (*Salmo salar*) is farmed in traditional open net cages. The fish are farmed as single production cycles with a four-month window for deployment of smolt and at least two months fallowing between farming cycles.

Planktonic Bivalvia larvae

Spatial and temporal variability of planktonic Bivalvia larvae was investigated during the summer 2018, 2019, and 2020. In the summer 2018 samples were only taken at station SO 6 while all five stations were investigated in 2019 and 2020 (Figure 1). In 2018 sampling took place from May to October, in 2019 from April to September and in 2020 from May to September.

At all stations, plankton was sampled by vertical hauls from 8 m dept to the surface, with an 80 µm mesh plankton net, with a 30 cm mouth diameter and length of 1.1 m. At stations SO 11, SO 6 and SO 2 additional vertical hauls were taken with a 150 µm mesh size plankton net (mouth diameter 50 cm and length 1.5 m) from 8 and 20 m depth. Both nets were equipped with a flow meter in order to calculate the volume of filtrated water. Samples were preserved in ethanol.

Bivalvia were identified and enumerated at the lab using a Leica M125 stereo microscope, usually within a week of sampling. Samples were split a few times depending on the quantity of zooplankton in the samples, and Bivalvia larvae were quantified using counting chambers.

Shell length was measured in samples at station S0 6 with the stereo microscope fitted with an eye-piece graticule calibrated for measurements in the counting chamber. Each larva was oriented and lined-up with the calibrated eye-piece graticule at x20 overall magnification (x10 eye-piece and x2 objective). The first ten Bivalvia larvae observed in each sample were measured.

Blue mussel settlement and growth trials

Two blue mussel farms were established in 2018 on mussel pipes produced by Hvalpsund Net A/S. The two farms consisted of ten 35 m long pipes with 50 cm between droppers that went down to 15 m depth.

Three types of droppers were tested with the aim to grow the mussels at the collectors without restocking with the primary purpose of IMTA bio-mitigation (Figure 3). Commercial droppers of Fuzzy Rope (FR) with led incorporated in the entire line, droppers composed of five meshes of trawl (TR) weighted down with metal at the bottom, and flat rope spat collectors usually used in Danish mussel farms “Svensker band” (SB) weighted down with metal at the bottom of the droppers.

Figure 3 Blue mussel farm at deployment, showing a mussel pipe with fuzzy rope droppers.

In 2018 the first farm was deployed from May 24th to May 30th, and the second from May 31th to June 8th. The lines were new and thus the earliest spat settlement should not be expected until two weeks later when a biofilm had established on the new material.

In 2019 most of the droppers were replaced with new droppers of FR and TR in late April to early May. The new FR droppers were 7.5 m long while the TR droppers were 15 m long, 7 meshes wide and equipped with heavier weight.

Two TR pipes and two FR pipes from 2018 were not replaced.

Samples were taken occasionally, to investigate the settlement and growth on the various types of droppers.

First investigations were conducted on June 26th when samples were taken semi quantitative to investigate early signs of spat settlement. Small samples of rope were taken at 1, 4, 8, 12 and 15 m depth and for each kind of spat settlement rope the samples were taken evenly. Although the samples were not quantitative, an effort was made to sample comparable volumes in order to make comparisons between the various settlement ropes.

All later samples were taken by rinsing a set length of line at 4, 8 and 12 m depth, and the number of samples and duration between sampling dates vas highly variable over time.

Statistics

T-tests were used to investigate if there were significant differences in numbers of larvae between the five stations (80 µm and 150 µm net), and possible differences in depth distribution at the stations where possible (150 µm net). Differences between the years was also investigated. Data from 2018 was taken into account only for station S0 6 at 8 m depth. Additionally, any significant difference in the size of the larvae in the the 80 µm net versus the 150 µm net at 8 m depth at station S06 was investigated (2019 and 2020 data). Differences in abundance of larvae from the innermost to the outermost part of the fjord, as well as north side versus south side of the fjord was also investigated.

Results

Shell length of planktonic Bivalvia larvae

There was a significant difference between the shell length of larvae sampled with the two mesh sizes (t-test, $p < 0.05$). Shell lengths ranged from ~ 120 µm to ~ 280 µm in samples taken with

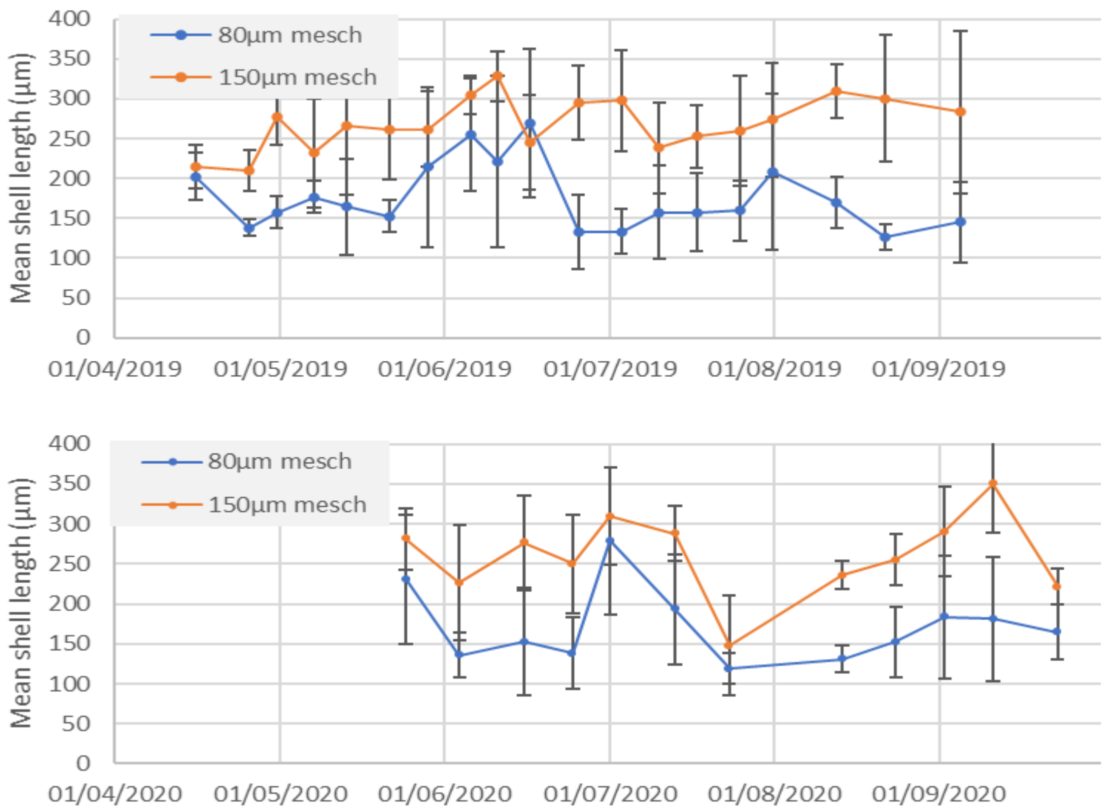


Figure 4 Mean shell length at station SO 6 from vertical hauls from 8 m depth to the surface with the 80 µm and 150 µm plankton net. Samples from 2019 are shown in the upper figure while the lower figure shows the samples from 2020. Error bars show the standard deviation.

the 80 µm net, and from ~ 150 µm to ~ 350 µm with the 150 µm net. The 150 µm mesh size net captured the largest larvae and the 80 µm mesh size net captured more of the smaller sized larvae, comparatively, although some larger larvae were found there too (Figure 4). This is of course expected but shows the overall size ranges of Bivalvia larvae in the area, using both mesh sized nets, during the time period sampled. The larval size shows the same seasonal pattern during both years, with increasing size until June-July and a second period with increasing size until August-September. However, there seems to be a delay in larval peak size in 2020 compared to 2019, peaks occur in June and August of 2019, and in July and September of 2020 (Figure 4).

Temporal variations in Bivalvia larval abundance

In general, the abundance of Bivalvia was considerably higher in the 80 µm net than the 150 µm net in the vertical tows from 8 m depth (Figure 5).

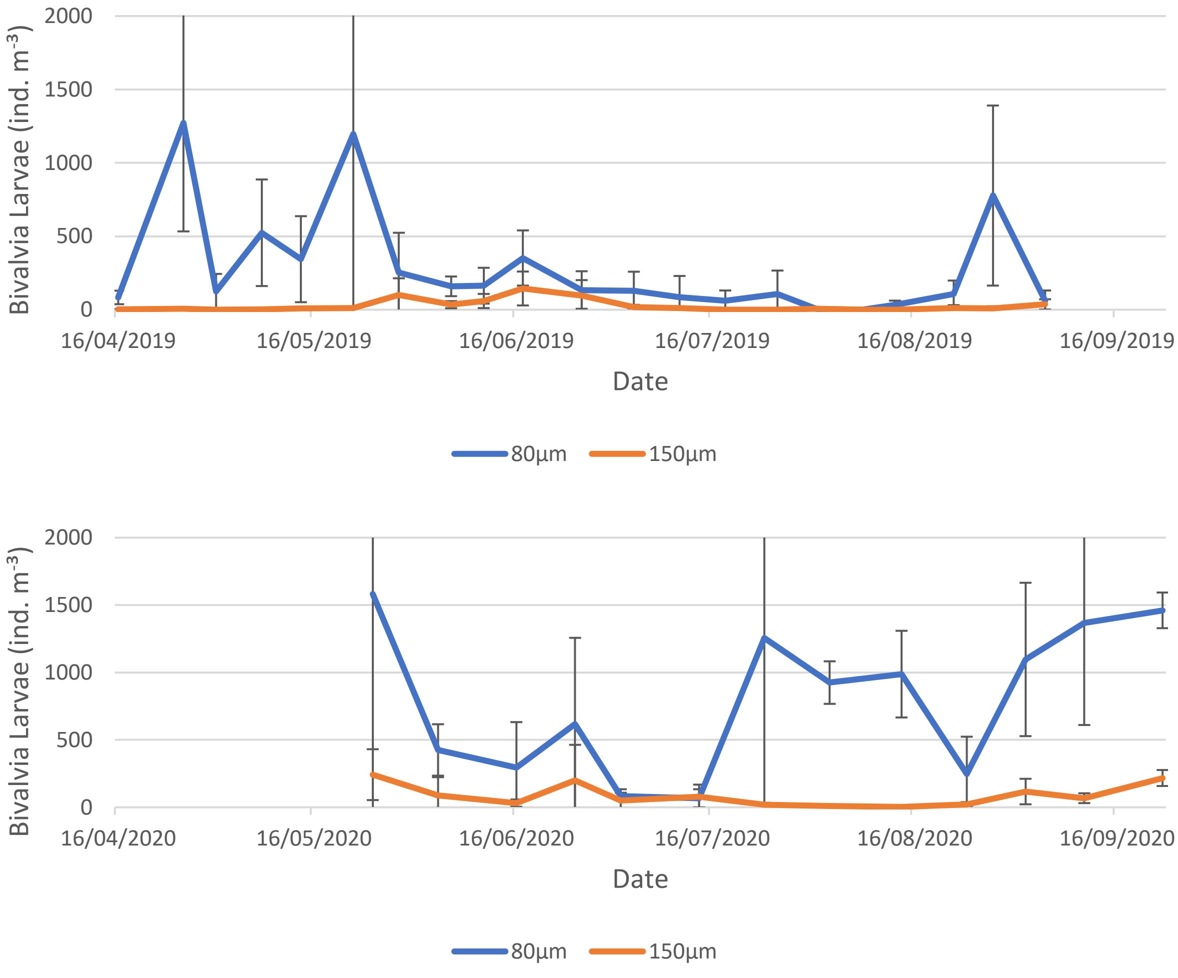


Figure 5 Mean abundance of planktonic larvae in the vertical hauls from 8 m depth to the surface at station SO 2, SO 6 and SO 11. The upper figure shows the abundance in 2019 and 2020 is shown in the lower figure. Error bars show the standard deviation between stations.

When tested individually and for each year, the abundance was significantly higher in the 80 µm samples than the 150 µm samples at all stations and both years with the exception of station SO 11 in 2019 (t-test,$p < 0.05$).

Both years showed two phases with high abundance separated by a period with general low abundances in mid-summer. The onset and duration of the phases did however vary as well as the measured peak abundances.

In 2019 there were four peaks in abundance in the 80 µm net, which occurred in late April, late May, mid-June and late August. In 2019 the maximum mean abundance in the 80 µm samples was 1272 ind. m^{-3} at 26/4-2019, whereas the maximum mean abundance for the 150 µm net was 144 ind. m^{-3} at 17/6-2019 at (Figure 5, upper figure).

In 2020 the first samples were collected in late May, when the 80 µm net mean abundance peaked with a maximum of 1582 ind. m^{-3}, two subsequent peaks occurred in 24/7-2020 and in 23/9-2020. For the 150 µm net there were three peaks; in late May, late June and late September. The maximum mean abundance for the 150 µm net was in 25/5-2020 at 242 ind. m^{-3} (Figure 5, lower figure).

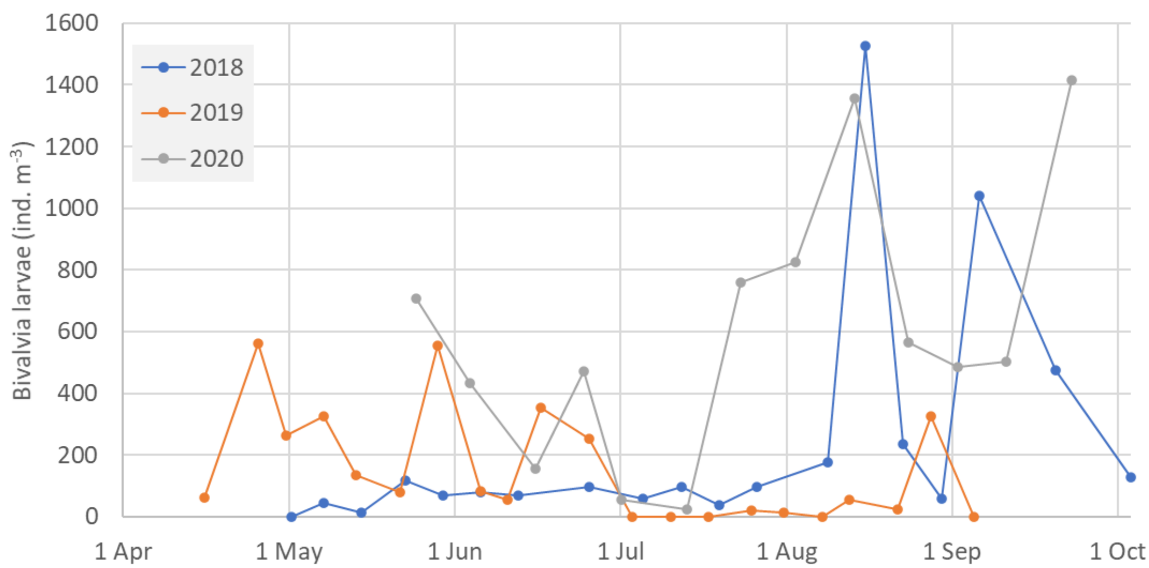
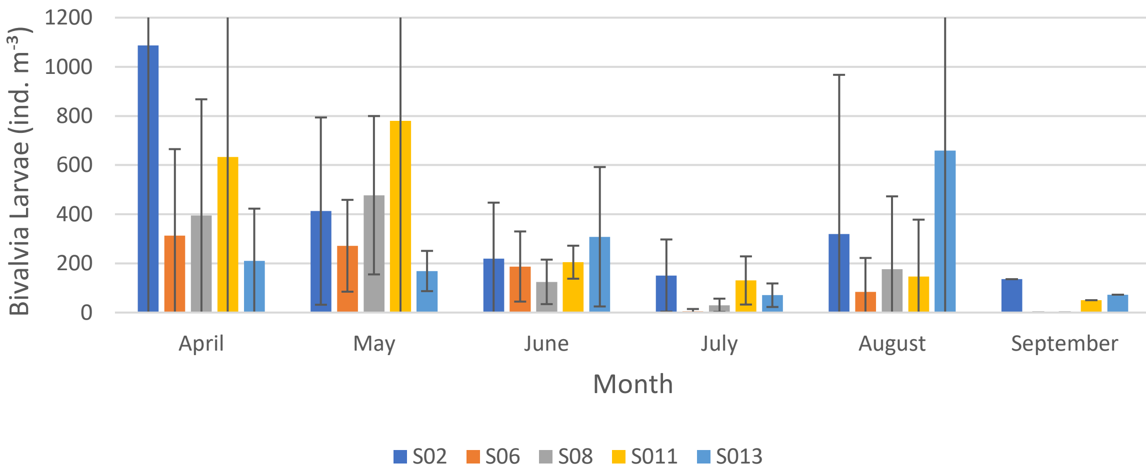


Figure 6 Bivalvia larval abundance at station SO 6 in 2018, 2019 and 2020. Samples were collected with the 80 µm plankton net at 0 – 8 m depth.

At station S0 6 which is in proximity to the long lines (Figure 1), samples were taken with the 80 µm plankton net in 2018 in addition to the other years. This gives the opportunity to investigate interannual variability for three years at the station (Figure 6). In 2018 the abundances were low during the entire spring and high densities were only found in august and September. In 2019 larvae were present from late April to late June and again in late August but the abundances were generally low with the first period having the highest abundances (max ~600 ind. m^{-3}). In 2020 the first peak is probably missed as sampling started to late relative to the spawning and the second peak started already in mid-July. Maximum abundances were observed in the second period in both 2018 and 2020 with 1525 ind. m^{-3} and 1358 ind. m^{-3} respectively.

Spatial variations in Bivalvia larval abundance

There was some variation in the number of larvae at the 5 sampling stations (Figure 7) as well as variations in seasonal abundances. However, there were no significant differences in abundance of larvae in the inner part of the fjord compared to the outer part, nor were there significant differences between the northern and southern part of the fjord. In general, the abundance was higher in 2020 than 2019 although the variance was quite high for both years.



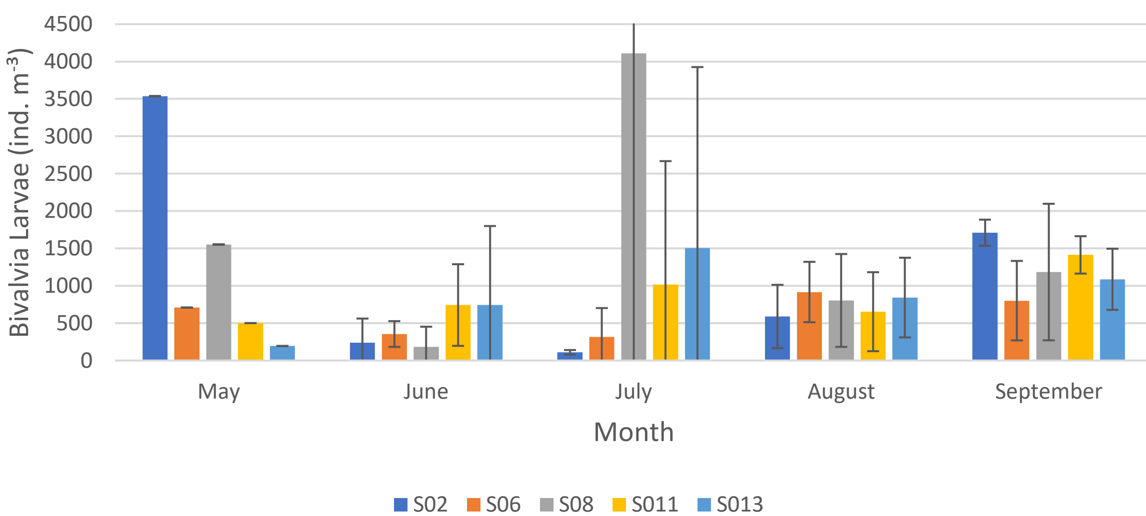


Figure 7 Mean monthly abundance of Bivalvia larvae at all stations in 2019 (upper figure) and 2020 (lower figure). Samples were collected with the 80 µm plankton net at 0 – 8 m depth. Error bars show the standard deviation between samples, and n~4 for each station per month.

None of the extreme peaks in larval abundance were observed at station SO 6 which is in proximity to the long lines (Figure 1) and in general the abundance there was in the lower end of observed larval abundances (Figure 7).

In addition to the vertical samples from 8 m depth, samples were taken with the 150 µm net from 20 m depth to the surface at stations SO 2, SO 6 and SO 11. The bottom depth at station SO 2 and SO 6 was around 25 – 30 m while it was highly variable between sampling dates at SO 11 due to the steep slope at the station (Figure 1).

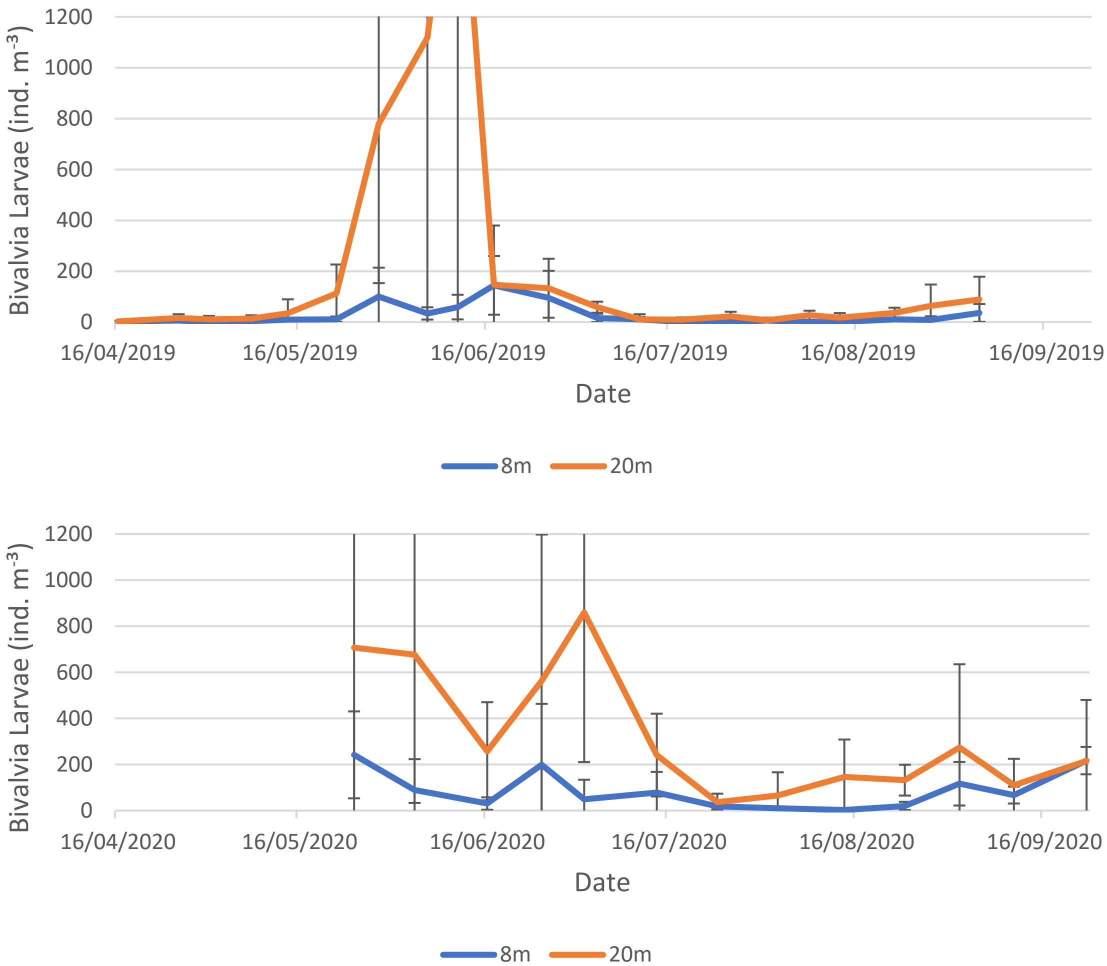


Figure 8 Mean abundance of planktonic larvae in samples collected with the 150 µm net at station SO 2, SO 6 and SO 11. The upper figure shows the abundance in 2019 and 2020 is shown in the lower figure. The blue line shows the abundance in the shallower tows (0 – 8 m) and the yellow line shows the abundance in the deeper tows (0 -20 m). Error bars show the standard deviation between stations. The value exceeding the y axis in the upper figure is 2030 ind. m^{-3}.

The mean abundance of Bivalvia larvae was higher in the vertical tows from 20 m depth than in the tows from 8 m depth (Figure 8), but the difference was only statistically significant at station

SO 2. The abundance was highest between late May and mid-June at both depths in 2019, with considerably higher abundance in the deeper samples. The peak mean abundance was at 2030 ind. m^{-3} on 11/6-2019 in the deeper tows while the peak abundance in the shallower tows was only 144 ind. m^{-3} and occurred on week later (Figure 8). The peak abundances occurred roughly when the size of the larvae was largest in mid-June (Figure 4). As these larvae settle, the abundance decreases again until there was a small increase again in late August – early September (Figure 8), corresponding to a secondary spawning event as mentioned earlier. The same trend was observed in 2020, although the peak mean abundance was considerably smaller with 860 ind. m^{-3} in 2/7-2020 in the deeper tows and 242 ind. m^{-3} in 25/5-2020 in the shallower tows (Figure 8).

Blue mussel settlement and abundance on longlines

The established blue mussels farm was intended to be low work load intensive, since the primary purpose of the blue mussels was mitigation of environmental impacts from fish farming. Thus, the aim was to establish a farm with passive spat collection and self-thinning. Three kinds of long lines were investigated Fuzzy rope (FR), Trawl (TR) and "Svendsker band" (SB). The first set of longlines were deployed in 2018 and the second deployment started in 2019. First investigations of settlement were conducted in late June 2018, this was done in order to investigate signs of preferred settlement depth, as the longlines were quite deep compared to other blue mussel farms. The samples were quite small and the total number of blue mussels was likewise small. No blue mussels were in the SB samples while they were present at all investigated depths in the FR and TR samples, with no clear signs of depth preferences.

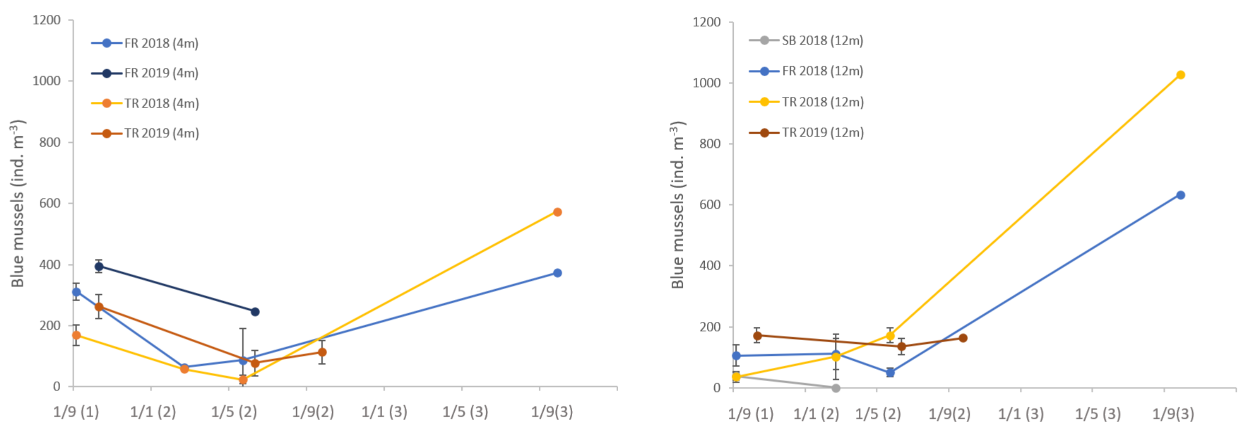


Figure 9 Blue mussel abundance over time on the three types of long lines at 4 m depth (left) and 12 m depth (right). The lines were deployed in 2018 or 2019. The number in brackets refers to years after deployment where (1) is the deployment year.

The settlement on the SB was quite low and when lines were investigated again later only sporadic blue mussels were observed, so it was decided to stop the trials with SB. For both deployments the highest settlement success was on the FR at 4 m depth (Figure 9, left figure), with slightly higher settlement in the 2019 deployment (395 ind. m^{-1}) compared to the 2018 deployment (311 ind. m^{-1}). However, for all the deployments the abundance at 4 m depth decreased during the first year. When the final investigation on the 2018 deployments were taken the abundances were higher than the initial settlement with more blue mussels on the TR (576 ind. m^{-1}) than FR (373 ind. m^{-1}). At 12 m depth the settlement was likewise higher in the FR (106 ind. m^{-1}) compared to the TR (36 ind. m^{-1}) in the 2018 deployment (Figure 9, right figure). The FR ropes only reached 7.5 m depth and thus no data is on the FR at 12 m dept for the 2019 deployment. The TR showed higher settlement success in the 2019 deployment (172 ind. m^{-1}) than in the 2018 deployments. At this dept the numbers were steadyr during the first year of deployment and when the final samples were taken in the third year the abundances were considerably higher with higher abundances on the TR (1026 ind. m^{-1}) than at the FR lines (633 ind. m^{-1}).

At the first sampling after deployment there was little variation in shell lengths which were 5 and 7 mm (Figure 10**Error! Reference source not found.**). During the deployments the variation in size increased considerably both within and between samples.

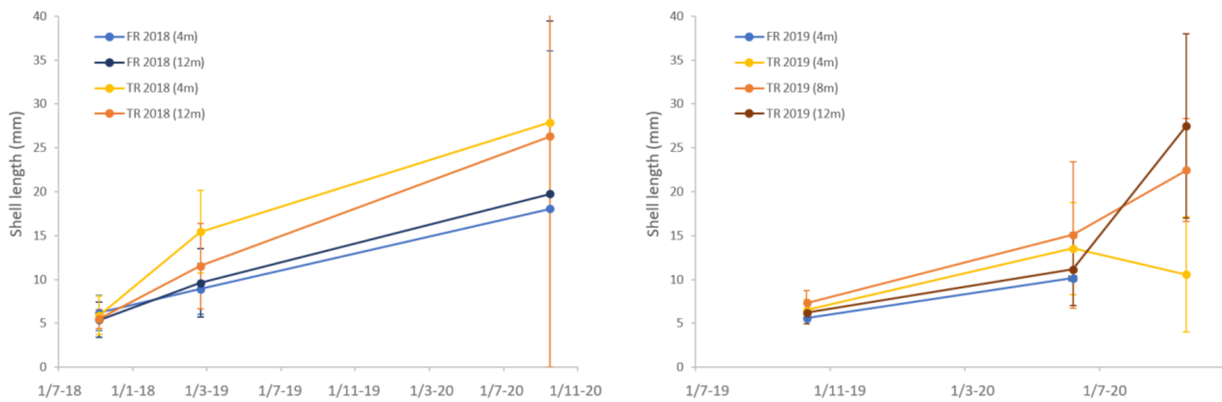


Figure 10 Average shell length at the various sampling dates on the longlines deployed in 2018 (left) and in 2019 (right).

The size distribution was investigated at three occasions during the first two years in the 2019 lines. At the first sampling date there was little size variation, and after one year before the new spat settlement was really visible, they were somewhat larger (Figure 11). In September 2020, after the second summer in the sea with visible new spat, the differentiation between depths started to show. At 4 m depth the abundance of newly settled spat was higher than the spat abundance from the previous year. Deeper on the TR ropes newly settled spat was only sporadic while the majority of the blue mussels were from the previous year (Figure 11).

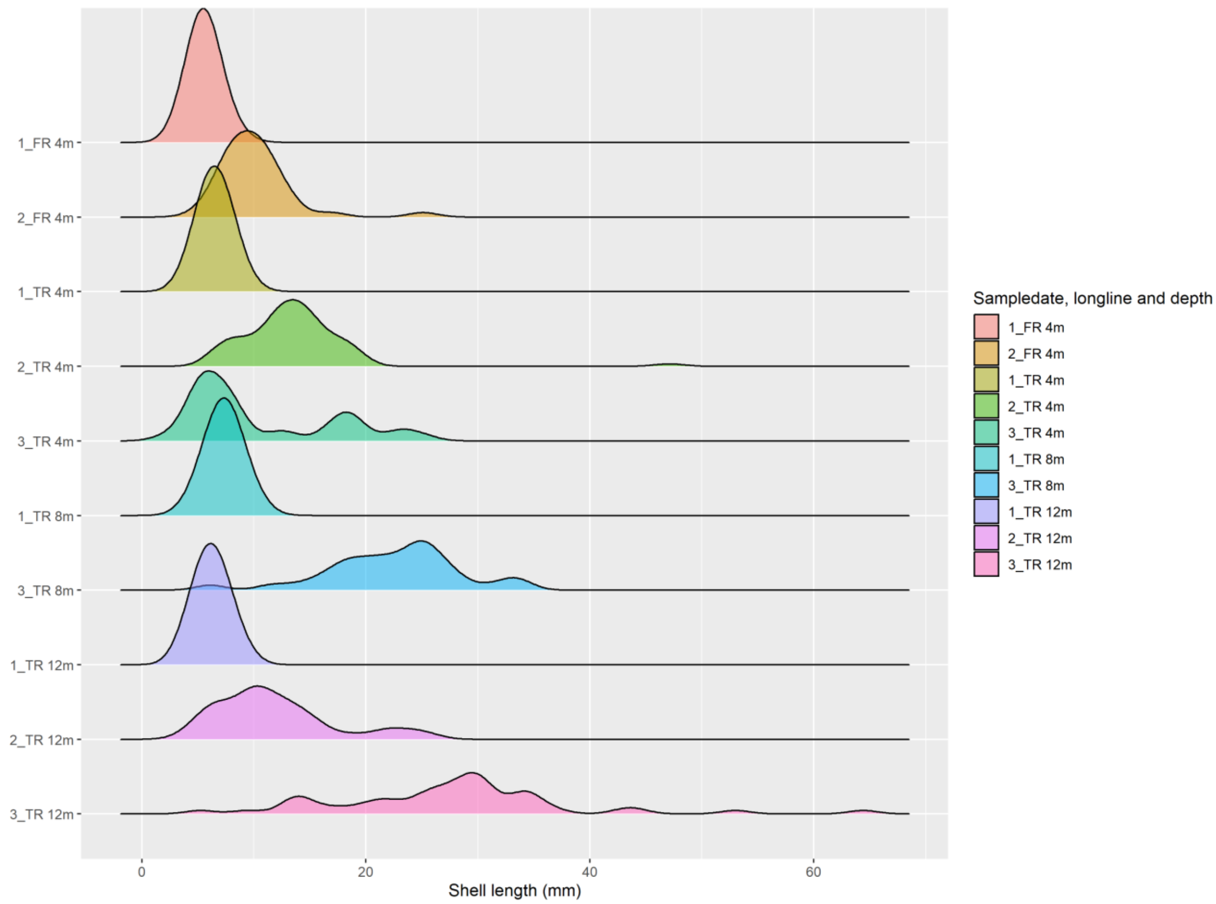


Figure 11 Size distribution of blue mussels on the longlines deployed in April-May 2019. The numbers refer to the sampling dates; 1(11/10-19), 2(11/6-20) and 3(23/9-20). The FR was only sampled on the two first dates.

After three years in the sea for the 2018 deployment, the average size of the blue mussels on the longlines was higher on the TR lines than at the FR lines with slightly larger mussels at 8 m than 4 m depth (Figure 12).The FR showed two peak abundances with newly settled spat (shell lengths of ~5-7 mm) spat from the previous year (~20 mm), while the TR lines only showed one peak with shell lengths from 20 to 30 mm. At 8 m depth on the TR lines, the most abundant size of mussels larger than 30 mm was 55 mm and they probably represent the majority of the spat from 2018. There were also some considerably larger blue mussels in the samples, especially on the deeper parts of the lines, and the largest mussels were 8.5 cm (Figure 12).

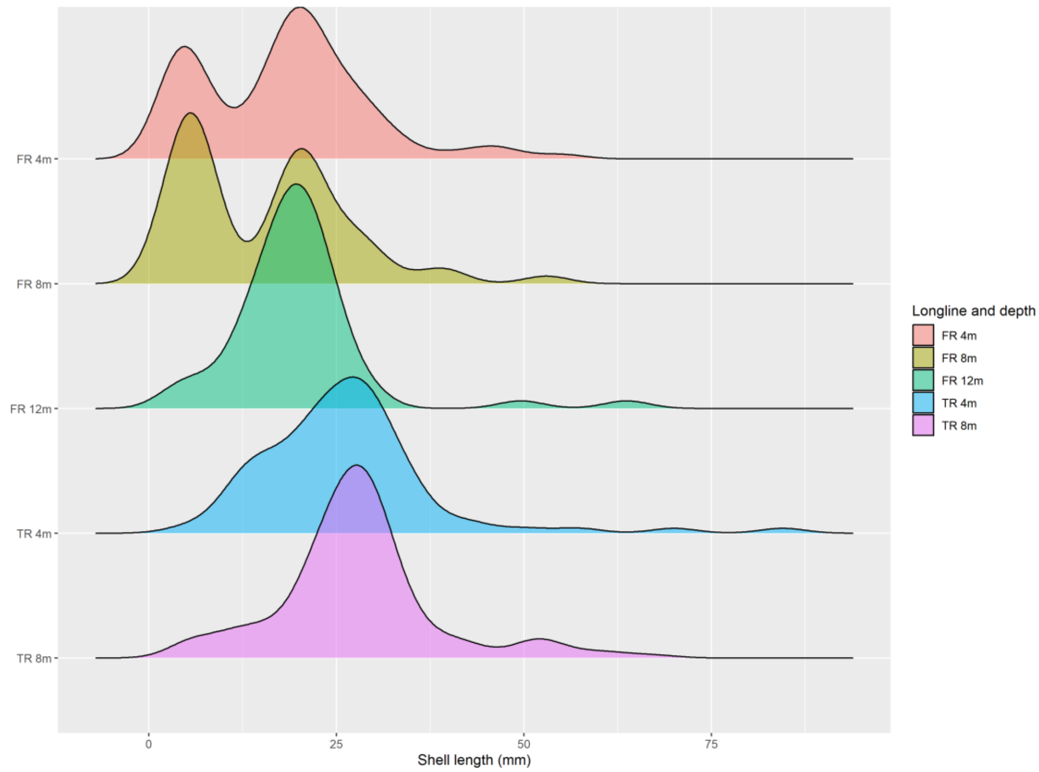


Figure 12 Density plots of the shell length distribution on the longlines deployed in 2018 as observed in September 2020.

In summary the mussels were largest and most abundant on the deeper part of the TR lines on the last sampling which was on the third year of deployment. Although not thoroughly quantified, the impression was that the TR lines showed a cleaner blue mussel culture than the FR lines, where there were a lot of various species present, and even some polychaetes.

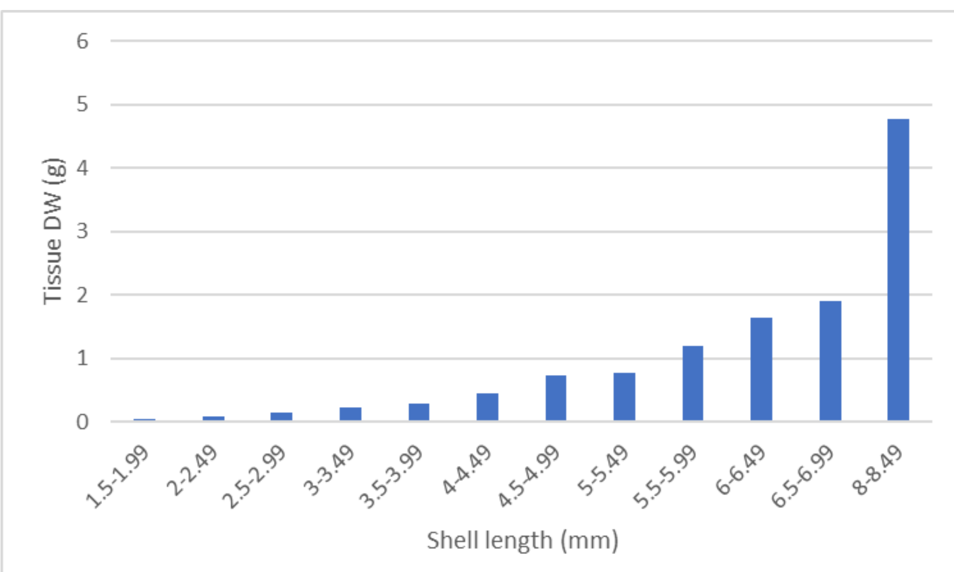


Figure 13 Tissue DW of various size classes of blue mussels on the longlines as measured in Septeber 2020. N = 10 for most samples.

The tissue DW of the various blue mussel sizes was investigated in September 2020. It was less than 1 g in sizes up to 5.5 cm while it was almost 5 g in the largest blue mussels (Figure 13).

Discussion

Shell length

Blue mussel larvae primarily settle when the shell length is ~ 260 µm (Bayne, 1965; Gazeau et al., 2010) but they can delay metamorphosis and remain in the planktonic compartment until they reach ~ 350 µm (Gazeau et al., 2010). However, results from many field and laboratory studies show that size at settlement varies (Ompi, 2011). For example, variation in size from 248 µm to 321 µm of larvae settling on different filamentous substrata in the laboratory was also reported (Eyster and Pechenik, 1988).

The observed drops in mean shell length after the peaks in late June early July presumably are due to larval settlement and/or predation, leading to smaller average larval sizes which then increase in size over time after spawning, and the pattern repeats itself.

In order to investigate the potential spat settlement, it is preferable that the nets target larva sizes just below the settlement size in order to minimise an overrepresentation of larvae that might be predated or flushed out of the fjord before they have reached settlement size or an underestimate if the targeted size is higher than the settlement size.

In this study, the larval abundance was significantly higher in the 80 µm mesh samples compared to the 150µm mesh samples (Figure 5), but the majority of the larvae in the 80 µm mesh were smaller than 200 µm and thus below the sizes reported at settlement while the size distribution in the 150 µm mesh was more compatible to sizes at settlement and may represent larvae in the water column ready to settle (Figure 14).

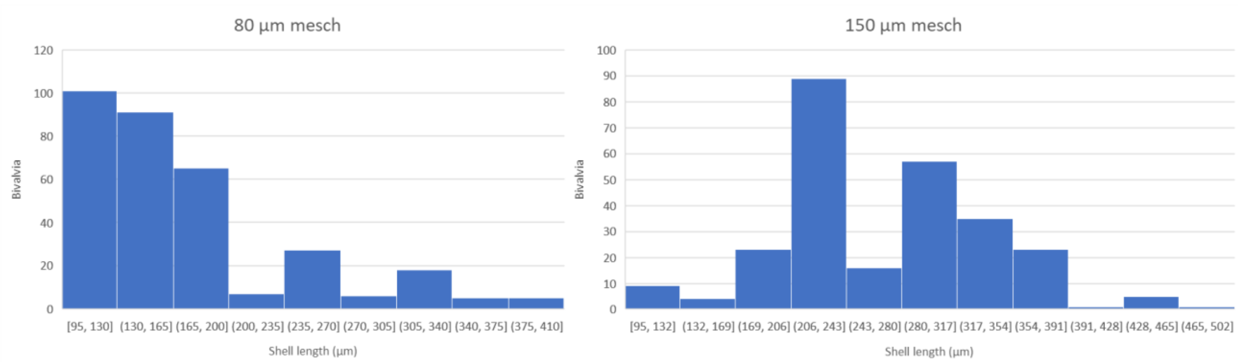


Figure 14 Histogram of the larval sizes distribution in samples from the 80 µm mesh net (left) and the 150 µm net (right).

Abundance

Mytilus edulis spawns from April to September, depending on water temperature, currents, and other environmental factors. In most populations, resting gonads begin to develop from October to November, with gametogenesis occurring throughout winter so that gonads are mature in early spring. A partial spawning in spring is followed by rapid gametogenesis, with gonads maturing by early summer, resulting in a less intensive secondary spawning in late August or September. Larvae spawned in spring can take advantage of phytoplankton blooms. Occurrence of the secondary spawning is opportunistic, depending on favourable environmental conditions and food availability (Pronker et al., 2008). The occurrence of two spawning events corresponds well with the observations of larval abundances and sizes, although the second spawning yielded higher abundances for two of the three investigated years (Figure 6).

Although showing a seasonal pattern, the reproductive cycle of *M. edulis* can exhibit considerable temporal and spatial variation. Gonads are usually ripe by early spring in European waters and mussels commonly show a significant loss of condition following spawning. Rapid gametogenesis leads to fully ripe gonads again in summer. Although directly driven by food availability and temperature, reproductive cycles in *Mytilus edulis* may vary latitudinally, both in terms of onset and duration (FAO). Additionally, the timing of the various components of the reproductive cycle differs greatly between various blue mussel populations within the North Atlantic and Mid-Atlantic regions. In habitats where annual variations in environmental factors are large, such as in estuaries with annually variable freshwater inputs, the reproductive cycle of *M. edulis* can be expected to vary (Newell, 1989). The interannual variability, in addition to the spring spawning and a secondary spawning in August-September, may be due to these factors (Figure 6).

In Knebel Vig, Denmark, the abundance of veligers in the summer period varied from 1.7–40.4 ind. l^{-1} in 1994 and 2.7–99.0 ind. l^{-1} in 1995 (Fotel et al. 1999). Moser (1996) reported 0–400 ind. l^{-1} from Limfjorden, Denmark. Schram (1968) reported 0–40 ind. l^{-1} from Oslo Fjord, Norway and Jørgensen (1981) reported up to 3000 ind. l^{-1} from Isefjorden, Denmark in 1941–42, although this is an extreme case. Our abundance varied from 0-12 ind. l^{-1} in the 80 µm mesh samples and was considerably lower in the 150 µm mesh samples. Thus, our observations are in the lower end of reported densities in other boreal neritic waters. However, Jensen and Patursson´s measurements, although not quantified, showed great variation between the different sites in the Faroe Islands (Jensen and Patursson, 2011).

Gaard measured larvae of 150 µm and larger, and collected down to a depth of 6.5 m. His investigations showed higher abundances than our observations with the same mesh plankton net down to 8 m depth. He reported one peak in June and one in August-September of approx. 350 ind. per m^3 in both cases, compared to ours of approx. 100 and 140 ind. per m^3 (late May and mid-June 2019), and approx. 240 and 200 ind. per m^3 (late May and late June 2020), with a secondary peak of approx. 215 ind. per m^3 (late September 2020) (Figure 8). In addition to the samples at 0-8 m depth, samples were also taken from 20 m depth to the surface with the 150µm mesch net. The bivalve density in those samples was considerably higher with a peak of 2030 ind. m-3 in early June 2019 (Figure 8), indicating that the Bivalvie larvae concentrations were considerably higher in the deeper layers.

It should, be noted that our numbers are from three sites within a fjord, and his numbers are from one location at the innermost part of a fjord. Thus, our sites were presumably more exposed. Jensen and Patursson (2011) reported highest larval abundance at approx. the same time we did; mid-May and late June. This was true for all locations except Skálafjørður, but they reported high concentrations of jellyfish in this fjord which may have had an effect on larval concentrations, as jellyfish prey on mussel larvae.

Our highest mean abundance measurement for the 80 µm net in 2019 was in April and May, decreasing for the rest of the summer until peaking again in late August. This corresponds to spring spawning, as well as a late secondary spawning, the decrease between late May and late August occurring due to settling, predation or the larvae are flushed out of the fjord. The peaks for the 150 µm net appear slightly delayed compared to the peaks of the 80 µm net, corresponding to larger Bivalvia size and settling (Figure 5). The results for 2020 regarding the 80 µm net, show a similar pattern with high production in the spring and late August – September, however the onset of a secondary production occurs already in late July. The abundance for the 150 µm net, however, was similar to that of 2019 (Figure 5).

It is possible that the lower abundance caught with the 150 µm net is due to settlement and/or predation. This is due to the size at which the larvae settle, as mentioned earlier, as well as the occurrence of filter feeders and other animals that prey on zooplankton, in the fjord.

As the results show a significant difference in numbers caught with the two nets, with a higher number caught with the smaller net, it is arguably preferable to use the 80 µm net when estimating the potential for bivalve settlement, as they represent larvae at sizes before settlement, also 80 µm mesh sizes have been recommend for identification purposes (Aucoin et al., 2004). However, the settlement potential might be highly overestimated since they may be predated or drift out of the fjord before they are mature for settlement. The 150 µm mesh samples on the other hand largely represented larvae at settlement size and also the larvae that have delayed metamorphosis thus the total potential larval settlement might be underestimated, since a portion most likely has already settled. The investigations also show that the sample depth can highly influence the results, as in this case with considerably higher Bivalvia abundance in the deeper waters than in the upper water masses (figure 8).

In this study the Bivalvia were not identified to species level, as identification of *M. edulis* is difficult due to the uniform morphology of many larval species (Hendriks et al., 2005). Up to about twenty other species belonging to Bivalvia have been found in other Faroese fjords (unpublished data). Thus, there is a degree of uncertainty regarding blue mussel larval abundance in this fjord. However, the only Mytilus species in the Faroe Islands detected so far is *Mytilus edulis* (Jensen and Patursson, 2011).

The finding of a significant difference in abundance between 8 m depth and 20 m depth (mesh size 150 µm) at S0 2, but not at S0 6 or S0 11 may be explained by a small gyre circulating counter clockwise in the inner part of the fjord, previously found (á Norði and Patursson, 2017). If the larvae are sinking in this area as they grow larger, and if at the same time they are not dispersed due to the gyre, this may explain the significant difference between the two depths at this station. Additionally, *Mytilus* spp. larvae tend to be distributed in the upper 8 m of the water column and settle mainly near the surface, but potentially migrate vertically in response to tides, phytoplankton abundance and haloclines (Yund et al., 2015). The same was not observed for S0 6 and S0 11 as these larvae are able to be dispersed by the currents. However, as there were no significant differences in abundance of larvae found from the innermost to the outermost part of the fjord, or north side versus south side of the fjord, the larvae appear to be uniformly distributed throughout the fjord. In other words, what matters more is the time of year (as well as variations between years), rather than specific locations in the fjord, regarding Bivalvia larvae.

Blue mussel settlement and abundance on longlines

The sudden drop in blue mussel larval sizes in mid-June early July in all three studies from the Faroe Island, indicate that the settlement from the first spawning occurs at this time.

The settlement of blue mussels in these trials was in the lower end of observations in the other trials in the Faroe Islands. In Trongisvágsfjørður, the highest settlement success (5100 ind. m^{-1}) was observed at the innermost part of the fjord. However, the number of settled blue mussels decreased fast towards the mouth of the fjord, with ~1000 ind. m^{-1} in the middle of the fjord, and almost no blue mussels at the mouth (Gaard, 1986). In Skálafjørður og Kaldbansfjørður there were ~700 ind. m^{-1}, while in the strait sundalagið at sites with strong tidal currents, one trial only showed sporadic blue mussels while the average abundance was ~200 ind. m^{-1} in the other trial (Jensen and Patursson, 2011).

The flat rope "Svenskerbånd" which is a highly successive spat collector used by blue mussel farmers in Denmark, did not perform well in these trials, but the Fuzzy rope and Trawl showed a better potential. The spat settlement was somewhat higher in the 2019 deployment than the 2018 deployment with ~100 more individuals per meter (Figure 9). The planktonic spat availability was also really low during spring and summer 2018 compared to 2019 indicating that few larvae from the first spawning were available in 2018 (Figure 6). The larval abundance from the second spawning was on the other hand considerably higher in 2018 than in 2019, so it is possible that the settlement from the second spawning was not observed in the September 2018 sampling due to small sizes, but the later samplings do not indicate that there was undetected spat in September since samplings later in the year showed fewer Bivalvia on the line in all samples except for the TR at 12 m (Figure 9).

The abundance of large planktonic larvae was considerably higher in the deeper tows than in the shallower ones (Figure 8), indicating that blue mussel spat availability was higher deeper in the sea, but the settlement trials always showed higher settlement on the shallower parts of the linens (Figure 9).

During the first year of deployment abundances were decreasing, especially at the shallower parts of the lines and after the spawning period the second year newly settled spat comprised a significant part of the blue mussels on the shallow part of the longlines, which is commonly observed as a result of physical disturbances, competition for space and predation (Karlsson-Drangsholt and van Nes, 2017). One of the most important predators on blue mussels are eider ducks, and although they can dive as deep as 50 m they generally prefer to dive shallower than 10 m (Varennes et al., 2013). The higher loss of blue mussels on the shallower part of the rope might be due to higher predation or higher mechanical disturbances close to the surface.

The blue mussel abundance after three years deployment is comparable to abundances observed on self-thinning long lines in Baie de Casapedia in Quebec after three years deployment. There the average blue mussel density was 590 and 1311 ind. m-1 on two tested lines (Lachance-bernard, 2008), and similar to this study the blue mussels covered a large size spectrum. However, the abundance of blue mussels in the larger size classes composed a larger fraction of the total number than in our study, with equal amounts of 2 cm and 5 cm large mussels, whereas the 2 cm mussels comprised the majority of the population in this study (Figure 12). The scarcity of the large mussels in this study might be a result of the low settlement success and subsequent losses during the first year of deployment.

The tissue dry weight content at size (Figure 13) was comparable to observations in other locations in the Faroe Islands (Jensen and Patursson, 2011) and in Nova Scotia, Canada (Mallet and Carver, 1993) but only half of that observed in Limfjorden in Denmark (Nielsen et al., 2016).

However, in Limfjorden the phytoplankton concentrations are high due to eutrophication and the blue mussel shells are often misshaped due to extremely high growth rates (Nielsen, personal communication).

The daily growth rate was approximated to be 0.03 to 0.04 mm day^{-1} by assuming July 1st to be the settling data and in order to reduce the bias from later settlements, excluding the mussels <10 mm after the second summer in sea and mussels <15 mm after the third summer. This is somewhat higher than growth rates reported in Nova Scotia (Mallet and Carver, 1993) and comparable to growth rates observed the first year of deployment in Kaldbaksfjørður, but considerably smaller than growth rates during the second year in Skálafjørður and Sundalagið (Jensen and Patursson, 2011).

In the study by Jensen and Patursson (2011). Chl. *a* concentrations remained high during all summer in all the fjords with an average summer concentration of 4.9 µg l^{-1}. This is comparable to conditions observed in Sørvágsfjørður in 2019 (Figure 15). In 2020 the Chl. *a* concentrations were below 4 µg l^{-1} at all observations after June 4th, 2020, but due to storage issues the samples from July and August were lost.

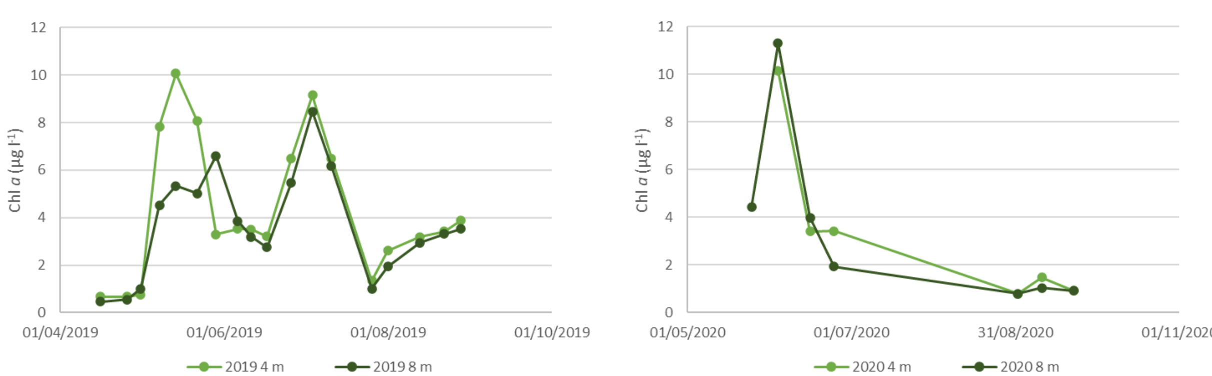


Figure 15 Chl. a concentrations at 4 and 8 m depth at the blue mussel farming site during summer 2019 (left) and 2020, (right).

However, the nitrate concetnrations do not indicate that there was a second Chl. *a* peak in 2020 as observed in 2019 (Figure 16). Assuming that Chl. *a* concentrations can be regarded as a proxy for food availability, than the food availibility during the second year of the 2019 deployment and third year of the 2018 deployment was considerably less than in the study by Jensen and Patursson (2011) and the lower growth rates might be related to that. In Nova Scotia, where the growth rates were somewhat smaller than in this study the Chl. *a* concentrations were less that 2µg l^{-1} during most of the summer (Mallet and Carver, 1993).

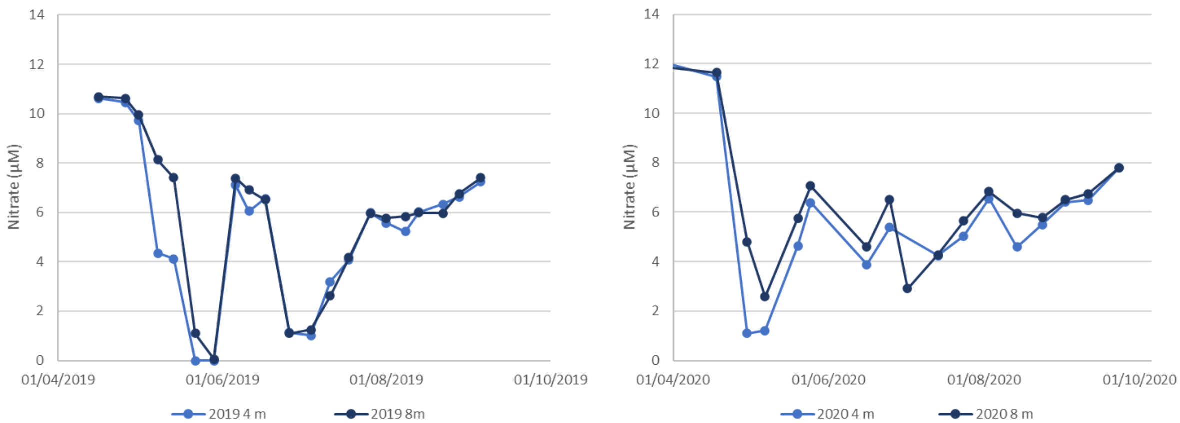


Figure 16 Nitrate concentrations at 4 and 8 m depth at the blue mussel farming site during sumer 2019 (left) and 2020 (right).

Conclusions

The abundance of planktonic Bivalvia larvae indicated two main spawning periods which is also the general observation from other studies. However, there was considerable interannual variability in the timing and density of blue mussels, and in two out of three years the abundance was higher during the second spawning that the first, which is opposite to many other observations. The size and density of planktonic Bivalvia indicated that most of the blue mussels from the first spawning period settled in mid-June to early July. The initial settlement of blue mussels on longlines was in the lower end of previous observations in the Faroe Islands, but during the continuous deployment the numbers increased, and after three years the density was within the range observed in other self-thinning longlines. Due to the continuous settlement on the lines, some assumptions were needed in the growth rate estimates. The growth rate between the first and second settlement thus was the most accurate estimate and it was similar to previous observations in the Faroe Islands. During subsequent years the growth rate was smaller than in other Faroese observations but higher than in areas with less phytoplankton and lower compared to areas with higher phytoplankton concentrations.

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